VU Research Portal

The effect of work pace on workload, motor variability and fatigue during simulated light assembly work

Bosch, T.; Mathiassen, S.E.; Visser, B.; de Looze, M.P.; van Dieen, J.H.

published in
Ergonomics
2011

DOI (link to publisher)
10.1080/00140139.2010.538723

document version
Publisher's PDF, also known as Version of record

Link to publication in VU Research Portal

citation for published version (APA)
Bosch, T., Mathiassen, S. E., Visser, B., de Looze, M. P., & van Dieen, J. H. (2011). The effect of work pace on workload, motor variability and fatigue during simulated light assembly work. *Ergonomics*, *54*, 154-168. https://doi.org/10.1080/00140139.2010.538723

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal ?

Take down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

E-mail address:
vuresearchportal.ub@vu.nl

Download date: 05. May. 2023

This article was downloaded by: [Vrije Universiteit Amsterdam]
On: 31 August 2011, At: 00:11
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

Ergonomics
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/terg20

The effect of work pace on workload, motor variability and fatigue during simulated light assembly work

T. Bosch [a b d], S.E. Mathiassen [b], B. Visser [c d e], M.P. de Looze [a c d] & J.H. van Dieën [c d]

[a] TNO, Quality of Life, PO Box 718, NL-2130 AS, Hoofddorp, The Netherlands

[b] Centre for Musculoskeletal Research, Department of Occupational and Public Health Sciences, University of Gävle, SE-80176, Gävle, Sweden

[c] Research Institute Move, Faculty of Human Movement Sciences, VU University, Amsterdam, 1081 BT, The Netherlands

[d] Body@Work, Research Center on Physical Activity, Work and Health, Amsterdam, The Netherlands

[e] Amsterdam School of Health Professions, University of Applied Sciences (HvA), Amsterdam/Academic Medical Center, University of Amsterdam, The Netherlands

Available online: 02 Feb 2011

To cite this article: T. Bosch, S.E. Mathiassen, B. Visser, M.P. de Looze & J.H. van Dieën (2011): The effect of work pace on workload, motor variability and fatigue during simulated light assembly work, Ergonomics, 54:2, 154-168

To link to this article: http://dx.doi.org/10.1080/00140139.2010.538723

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching and private study purposes. Any substantial or systematic reproduction, re-distribution, re-selling, loan, sub-licensing, systematic supply or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

Ergonomics
Vol. 54, No. 2, February 2011, 154–168

Taylor & Francis
Taylor & Francis Group

The effect of work pace on workload, motor variability and fatigue during simulated light assembly work

T. Bosch[a,b,d]*, S.E. Mathiassen[b], B. Visser[c,d,e], M.P. de Looze[a,c,d] and J.H. van Dieën[c,d]

[a]*TNO, Quality of Life, PO Box 718, NL-2130 AS Hoofddorp, The Netherlands;* [b]*Centre for Musculoskeletal Research, Department of Occupational and Public Health Sciences, University of Gävle, SE-80176 Gävle, Sweden;* [c]*Research Institute Move, Faculty of Human Movement Sciences, VU University, Amsterdam 1081 BT, The Netherlands;* [d]*Body@Work, Research Center on Physical Activity, Work and Health, Amsterdam, The Netherlands;* [e]*Amsterdam School of Health Professions, University of Applied Sciences (HvA), Amsterdam/Academic Medical Center, University of Amsterdam, The Netherlands*

(*Received 23 December 2009; final version received 23 October 2010*)

This study investigated the effect of work pace on workload, motor variability and fatigue during light assembly work. Upper extremity kinematics and electromyography (EMG) were obtained on a cycle-to-cycle basis for eight participants during two conditions, corresponding to "normal" and "high" work pace according to a predetermined time system for engineering. Indicators of fatigue, pain sensitivity and performance were recorded before, during and after the task. The level and variability of muscle activity did not differ according to work pace, and manifestations of muscle fatigue or changed pain sensitivity were not observed. In the high work pace, however, participants moved more efficiently, they showed more variability in wrist speed and acceleration, but they also made more errors. These results suggest that an increased work pace, within the range addressed here, will not have any substantial adverse effects on acute motor performance and fatigue in light, cyclic assembly work.

Statement of Relevance: In the manufacturing industry, work pace is a key issue in production system design and hence of interest to ergonomists as well as engineers. In this laboratory study, increasing the work pace did not show adverse effects in terms of biomechanical exposures and muscle fatigue, but it did lead to more errors. For the industrial engineer, this observation suggests that an increase in work pace might diminish production quality, even without any noticeable fatigue being experienced by the operators.

Keywords: work pace; industrial ergonomics; variability; electromyography; fatigue

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

1. Introduction

During recent decades a number of studies have identified generic occupational risk factors that are associated with musculoskeletal disorders in the arms, shoulders and neck. In the biomechanics domain, high external force demands, high movement velocities and accelerations of movements, repetitive movements and prolonged activity with little variation ('static loads') have been identified as generic risk factors at the individual level (Kilbom 1994, Bernard 1997, National Research Council/Institute of Medicine 2001). Furthermore, several studies have established that a number of factors inherent to the organisation of work are associated with increased risks of developing musculoskeletal disorders in the upper extremity, probably by modifying the levels, frequencies and/or durations of exposure to the generic risk factors. These organisational determinants include overtime (Bergqvist *et al.* 1995), long working hours (Trinkoff *et al.* 2006) and a high work pace (HWP) (Houtman *et al.* 1994).

In cyclic work, work pace is inherently linked to the frequency of repetitive movements (Andersen *et al.* 2003). However, while work pace is therefore claimed to be important to the risk of developing musculoskeletal disorders, it has received little attention in experimental research. Only a few studies have investigated the acute effects of work pace in an occupational setting (Arndt 1987, Odenrick *et al.* 1988) or in controlled experiments (Sundelin 1993, Mathiassen and Winkel 1996, Laursen *et al.* 1998, Visser *et al.* 2004, Selen *et al.* 2006). In general, these studies showed that a higher work pace was associated with higher levels of shoulder muscle activity, signs of muscle fatigue and an increase in perceived discomfort.

Since work pace relates directly to productivity, it is also of prominent importance in an engineering context (Wells *et al.* 2007). This applies to any kind of production system, but is particularly evident in flow-type production, such as an assembly line in the

*Corresponding author. Email: tim.bosch@tno.nl

ISSN 0014-0139 print/ISSN 1366-5847 online
© 2011 Taylor & Francis
DOI: 10.1080/00140139.2010.538723
http://www.informaworld.com

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

manufacturing industry. In this case, the line is typically designed to operate at a certain cycle time, controlled by machines or by operators. Optimal system performance not only requires the target pace to be reached at each workstation on average, but it also relies on operators showing minimal temporal variability in work pace. Cycle time variability between and within individuals inevitably leads to time losses, in particular for lines without buffers between stations (Wild 1994). Engineers in the manufacturing industry often use predetermined time systems (e.g. Methods–Time Measurement, Ready Work Factor (RWF)) when determining a target work pace, but these standards do not account for the effects of between- and within-subject variability on time losses in the production system. The between- and within-subject variability in assembly work pace is, however, considerable (Dempsey and McGorry 2004, Möller *et al*. 2004, de Looze *et al*. 2005) and so the strive for a stable cycle time presents a genuine challenge to engineers.

In addition to this temporal variability, all cyclical activities show kinetic and kinematic variability between cycles. This 'motor noise' is an inherent property in sensorimotor control and so it appears in very stereotyped tasks such as gait (e.g. Terrier and Schutz 2003), as well as in occupational tasks of differing complexity (e.g. Hammarskjöld *et al*. 1989, van Dieën *et al*. 2001, Mathiassen *et al*. 2003, Madeleine *et al*. 2008b, Jackson *et al*. 2009). Motor variability is of interest to the engineer to the extent that it may interfere negatively with performance in terms of quality and error rate, even if not all kinematic and kinetic variability will have adverse effects on target performance (Domkin *et al*. 2005). From an ergonomic viewpoint, on the other hand, motor variability has been suggested to be generally beneficial to the physiological and medical outcome of physical work, in being an intrinsic source of exposure variation (Mathiassen 2006), allowing tissues to temporally recover from preceding exposures (Bongers *et al*. 2002, Järvi and Uusitalo 2004).

In the shoulder region, variability appears possible, and present, at the level of individual motor units (Thorn *et al*. 2002), between parts of the same muscle (Mathiassen and Winkel 1990, Jensen and Westgaard 1997) and among different muscles with similar biomechanical functions (Palmerud *et al*. 1995). Laboratory studies have suggested that individuals differ in the size of this motor variability and that a larger variability is associated with attenuated development of fatigue (van Dieën *et al*. 1993, Mathiassen and Aminoff 1997, Farina *et al*. 2008). Motor control research even suggests that variability can be trainable (Wilson *et al*. 2008). In low-level, long-lasting tasks, exposure variation may therefore be increased, with expected beneficial effects, by promoting an individual's ability to perform his/her work using different motor solutions, in addition to implementing organisational measures such as job rotation or increased break allowances (Straker 2003, Mathiassen 2006, Wells *et al*. 2007). Determinants of motor variability have lately received increased attention in occupational research (e.g. Madeleine *et al*. 2008a,b, Madeleine and Madsen 2009), as well as in sports science (Bartlett *et al*. 2007).

Since, as mentioned above, work pace influences biomechanical exposure levels (Odenrick *et al*. 1988, Sundelin 1993, Mathiassen and Winkel 1996, Laursen *et al*. 1998), it may well be a determinant of motor variability, but this has, to the present authors' knowledge, not been investigated in an occupational context.

The present study investigated the effect of work pace on motor patterns in a light, simulated assembly task by assessing the level and cycle-to-cycle variability of a number of parameters describing upper extremity kinematics and muscle activity. The effect of work pace on physiological responses was also addressed through recordings of maximum force generating capacity, electromyographic (EMG) manifestations of muscle fatigue, pressure pain threshold (PPT) and perceived fatigue.

2. Method

2.1. *Participants*

Eight right-handed, healthy females (mean age 20.5 (SD 1.8) years, weight 61.1 (SD 12.1) kg, height 1.69 (SD 0.05) m, BMI 21.3 (SD 3.6) kg/m^2) volunteered to participate in the study. Exclusion criteria were disorders or pain in the neck and shoulder region. Participants were asked to avoid heavy exercise of the arms during the week preceding the study. All participants gave their written informed consent prior to the start of the study. The study was approved by the local ethics committee.

2.2. *Procedure*

The participants performed a 2-h pick and place task at two work paces (see below) on two different days with 1 or 2 d in between. The order of the two work paces was, to the extent possible, randomly assigned to a particular participant, while securing a balanced design of task order between subjects. To ensure familiarity with the task and to offset a learning effect across trials, a training session was performed 1 d before the first work pace experiment. Training was carried out at the HWP (described below) and lasted until a stable work rhythm was achieved, 1 h as a

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

minimum. All sessions were performed in a laboratory at a constant ambient temperature of 22°C. The task was performed with both hands, but given that the dominant arm is more fatigue-resistant than the non-dominant arm (Farina *et al.* 2003), electromyography, kinematics and PPT were only measured for the non-dominant side.

2.3. Task

The task involved repetitive pick and place actions so as to simulate industrial assembly. The task was performed using a Perdue pegboard (Purdue Pegboard Model 32020; Lafayette Instrument Company, Lafayette, IN, USA) centrally positioned in front of the participant. Participants had to pick, place and remove three pins, three collars and three washers in a fixed order with the left and right hand simultaneously. Bins with these components were placed to the left and the right of the participant (Figure 1). At the start and end of each cycle, participants had to move the pegboard to a fixed position and push a button in front of them. Participants were free to choose their own working technique and were instructed only on the sequence of actions. First, sitting height was individually adjusted to obtain a knee angle of 90°. After that, working height was standardised by placing the table surface 5 cm below the position of the wrist when the elbow was 90° flexed and the participant sat in an upright position. Table and chair height were noted at the first experiment and reused in the second. An auditory signal was given by a clock at the intended completion of each cycle and participants were asked to keep to the cycle time as closely as possible.

Work pace was calculated using the RWF analysis, a predetermined time system for predicting standard times in new or existing jobs (Niebel and Freivalds 2003). On the basis of the RWF analysis, a 'low' work pace (LWP) condition was selected, which the participants were expected to be able to perform efficiently and without errors after a short training session. The LWP was set at a cycle time of 48 s and could be seen as a 'normal' work pace according to industrial time standards. A HWP condition was selected so as to represent a difficult and stressful task for the participants. The HWP cycle time was set at 38 s, i.e. equivalent to 126% of the pace in the LWP condition, and it represents a realistic work pace in the manufacturing industry.

2.4. Measurements

2.4.1. Kinematics

3-D postures and movements were recorded using Optotrak (Northern Digital Inc., Waterloo, Ontario, Canada), sampling rate 200 samples/s. Markers were placed on the left arm and shoulder at the styloid process of the ulna, the epicondylus of the humerus and at the acromion. Reference markers were placed on one of the bins and at the button in front of the participant. The marker positions were marked with a waterproof pencil, in order to place the markers at exactly the same position in both conditions. The data were low-pass filtered with a Butterworth filter (second order, cut-off frequency 10 Hz).

Short periods (<0.5 s) with missing values for shoulder, elbow or wrist data were replaced by spline interpolation or estimates on the basis of available data. On the basis of the wrist kinematics measurements, the dynamic movements when lifting and transferring the pegboard at the start and end of each cycle were identified and used to eliminate these parts of the cycle from further analysis. Thus, further analysis focused on the assembly part of the cycle, i.e. pick and place small components. This part lasted 40.9 s and 32.3 s in the LWP and HWP conditions, respectively, according to the RWF analyses. For each assembly cycle, the following measures were obtained using custom scripts in MATLAB (The MathWorks, Inc., Natick, MA, USA):

Figure 1. Workstation set-up.

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

- Distance covered, i.e. the distances travelled by the wrist, elbow and shoulder relative to the button in front of the participant. Because of missing values due to markers that were obscured from the sight of the camera, the average movement speed over each cycle within the available episodes of data was calculated. Subsequently, the weighted mean speed over all episodes was determined and the distance covered was calculated by multiplying the weighted mean speed with the exact cycle duration.
- Average speed, i.e. the mean value across the assembly cycle of the derivatives of the wrist, elbow and shoulder distance.
- The root mean square of the total acceleration time series of the wrist, elbow and shoulder; acceleration being obtained as the second derivative of distance.
- The average 3-D shoulder position relative to the button in front of the participant.

The distance covered by the wrist relative to the shoulder was calculated to obtain a measure of total arm movement. The position of the wrist relative to the shoulder position was therefore used. The distance covered by the wrist relative to the elbow position was calculated to evaluate the contribution of the forearm to the distance covered by the wrist. The contribution of the upper arm to the wrist distance was expressed through the position of the elbow relative to the position of the shoulder.

2.4.2. *Surface electromyography*

Deltoid and forearm extensor electromyography was measured by a porti 16/ASD system (TMS, Enschede, The Netherlands). Bipolar Ag/AgCl (Medicotest; Ambu A/S, Ballerup, Denmark) surface electrodes were positioned according to Hermens *et al.* (2000); however, using an inter-electrode distance (IED) of 25 mm. A reference electrode was placed on the C7 spinous process. Before the electrodes were applied, the skin was shaved, scrubbed and cleaned with alcohol. EMG signals were continuously sampled during the entire work bout at a sampling rate of 1000 samples/s and band-pass filtered (10–400 Hz).

Electromyography from the left trapezius, pars descendens, was recorded using a linear adhesive array of eight electrodes (bar electrodes, 5 mm $\times$ 1 mm size, 5 mm IED ; LISiN-SPES Medica, Milan, Italy). Prior to electrode placement, the descending part of the trapezius was assessed during preliminary test contractions with a dry array of eight electrodes (silver bars, eight electrodes, 10 mm IED) as previously described by Farina *et al.* (2002). The main muscle innervation zone location was identified for the trapezius muscle from the surface EMG recordings. The skin was gently abraded and cleaned with water. The adhesive array was positioned between the detected innervation zone location and the distal tendon region of the muscle aligned along a straight line between the acromion and the C7 spinous process (Jensen *et al.* 1993). A reference electrode was placed at the right sternum. All EMG electrode positions were marked with a waterproof pencil, in order to exactly reproduce the electrode placement in both work pace conditions. Upper trapezius EMG was amplified 5000 times (64-channel surface EMG amplifier, SEA64, LISiN-OT Bioelectronica, Torino, Italy; 3-dB bandwidth, 10–500 Hz), sampled at 2048 samples/s and A/D converted in 12 bits (National Instrument® acquisition board, Austin, TX, USA).

For each work cycle, the mean EMG amplitude of the deltoid and forearm extensors was determined by averaging the band-pass filtered (10–400 Hz) and rectified signal, obtained by taking the absolute value of the each sample. The mean power frequency (MPF) was calculated using Welch's method (Welch 1967). For the linear electrode array on trapezius, the average values of the amplitude and MPF over the mid four to five channels were calculated. The outer channels were excluded from analysis due to low signal to noise ratios for almost all trials. For all muscles, EMG amplitudes were normalised using a maximum voluntary excitation (MVE) procedure (Mathiassen *et al.* 1995). Maximal EMG amplitudes were obtained from two 5-s maximum voluntary contractions (MVCs) performed against manual resistance at the start of each experimental day. Each MVC was followed by a rest period of at least 1 min. A 1-s moving window was used to determine the maximum rectified and averaged value for each muscle across both MVCs.

2.4.3. *Maximum voluntary force*

The maximum voluntary force (MVF) was determined while the participant was seated on a chair with the knees flexed at 90°. Adjustable straps were positioned over the middle of the upper arms, with the participant maintaining a maximally upright position of the upper body. The participants were asked to perform maximal abduction of both arms against the resistance provided by the straps for 4 s. To obtain MVF, a strain-gauge force transducer (model FP11463–00533-B; Futek, Irvine, CA, USA) was connected to the left strap. Force data were sampled with 1000 samples/s and averaged over the sample period. The maximal force over three trials was considered to be the MVF. Each trial was followed by a short rest period. The MVF was measured directly before and after the experimental task.

2.4.4. *Performance*

The total cycle time was determined from the button trigger signal. The actual cycle time of the assembly part was derived from the kinematic data as described above. Furthermore, work quality was measured by the average number of errors per 10-min period, as observed by the experimenter. An error was defined as an action not accounted for in the RWF analysis (e.g. dropping a component).

2.4.5. *Perceived fatigue*

Perceived muscle fatigue in the neck and shoulder area was rated every 15 min during the trial using the CR-10 Borg scale (Borg 1982, Åhsberg and Gamberale 1998, Strimpakos *et al.* 2005). The participant was acquainted with the Borg scale during the training session.

2.4.6. *Pressure pain threshold*

PPT in the upper trapezius and deltoid muscle regions was measured before and after each trial by use of an algometer (FPK 20, 20Lb × 25Lb; Activator Methods, Phoenix, AZ, USA) as previously described (Mathiassen and Winkel 1996). Recordings of PPT in the shoulder region have been used extensively to evaluate changes in soreness in experimental (e.g. Nakata *et al.* 1993, Mathiassen and Winkel 1996, Hidalgo-Lozano *et al.* 2010) as well as clinical (e.g. Mathiassen *et al.* 1993, Nielsen *et al.* 2010) studies, based on the notion that a changed PPT is a relevant indicator of altered pain perception (Fischer 1987). The participant was asked to give a signal when the perception changed from 'pressure' to 'pain'. The corresponding pressure value (Pa) was noted as the participant's PPT. Two determinations of threshold were made and their average was used as the subject's PPT.

2.5. *Cycle-to-cycle variability*

Cycle-to-cycle variability was expressed in terms of the median absolute deviation (MAD), as described by Shevlyakov and Vilchevski (2002). As indicated by its name, this estimator is the median of the absolute differences between individual sample values and their common median. This estimator of variability is more robust to outliers than the standard deviation or the coefficient of variation (Chau *et al.* 2005). Cycle-to-cycle variability was calculated for all EMG (amplitude and MPF) and kinematic (distance covered, speed and acceleration of the wrist, shoulder position) parameters.

2.6. *Statistical analysis*

Differences between the HWP and LWP conditions in mean cycle time, levels of EMG and kinematic variables were analysed using Wilcoxon signed rank tests, i.e. using participants as their own controls. Differences in cycle-to-cycle variability for cycle time and EMG and kinematic variables, as expressed by the MAD, were also analysed using Wilcoxon signed rank tests. Perceived fatigue (conditions), PPT, error (conditions) and maximum shoulder force data were analysed using a Wilcoxon signed rank test. Error data were analysed with Friedman's ANOVA for repeated measures to assess the effects of the independent variable time (12 blocks of 10 min each) on the average number of errors and rating of perceived fatigue. Significance was accepted at $p < 0.05$.

3. Results

The average assembly cycle time differed significantly – as intended – between the LWP and HWP conditions ($p = 0.012$, $Z = 2.52$) and both were very close to the pre-determined time standard set by the RWF system, i.e. 40.7 s and 32.4 s, respectively. Cycle time variability did not differ significantly between paces (MAD = 1.19 and 1.27 for the LWP and HWP, respectively; $p = 0.48$, $Z = 0.70$).

Ideally, the protocol would result in 190 and 150 complete cycles for each participant in the HWP and LWP condition, respectively. However, due to insufficient quality of the recordings of deltoid and forearm electromyography and of kinematic data, on average 178 and 140 cycles per participant were accepted for further analysis in the two conditions. Missing values were mainly due to poor visibility of the reflective markers. For the multi-array trapezius electromyography, insufficient recording quality led to only 156 and 122 cycles, on average, being included for the HWP and LWP conditions, respectively.

3.1. *Workload*

The average EMG activity levels for the upper trapezius muscle were 12.4%MVE (HWP) and 9.2% MVE (LWP), as shown in Figure 2. The deltoid muscle showed an average activity of 5.1%MVE and 5.5% MVE and the forearm extensor muscle activity was 6.2% MVE and 5.0% MVE (Figure 2) in the HWP and LWP condition, respectively. None of the

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

differences between conditions was statistically significant.

Analysis of the kinematic data showed that the wrist was moved more efficiently during the HWP condition, as indicated by a 6% shorter distance covered (Table 1; $p = 0.012$, $Z = 2.52$). As expected, the average speed and acceleration of the wrist were higher during the HWP condition (Figure 3a; $p = 0.012$, $Z = 2.52$ and $p = 0.017$, $Z = 2.38$, respectively).

The distance covered by the elbow relative to the wrist was calculated as a measure of the contribution of the forearm to wrist movement (Table 1). This distance was significantly shorter at the HWP ($p = 0.012$, $Z = 2.52$). The contribution of the upper arm to wrist movement was expressed as the movement of the elbow relative to the shoulder and, again, the distance was shorter for the HWP (Table 1; $p = 0.017$, $Z = 2.38$). However, the relative contributions of upper and forearm movement to the distance travelled by the wrist did not change with work pace. The pattern of arm movement was therefore independent of work pace.

No significant difference between the HWP and LWP was found for the distance covered by the shoulder during a work cycle ($p = 0.78$, $Z = 0.28$). The shoulder was, however, placed in a significantly more forward ($p = 0.017$, $Z = 2.38$) and lower ($p = 0.036$, $Z = 2.10$) position during HWP than during LWP (Figure 4a). However, time series of shoulder positions differed substantially between participants (for an example, see Figure 5). It appeared that some participants showed clear temporal changes while others had a stable shoulder position. No systematic differences were found between the HWP and LWP in this respect.

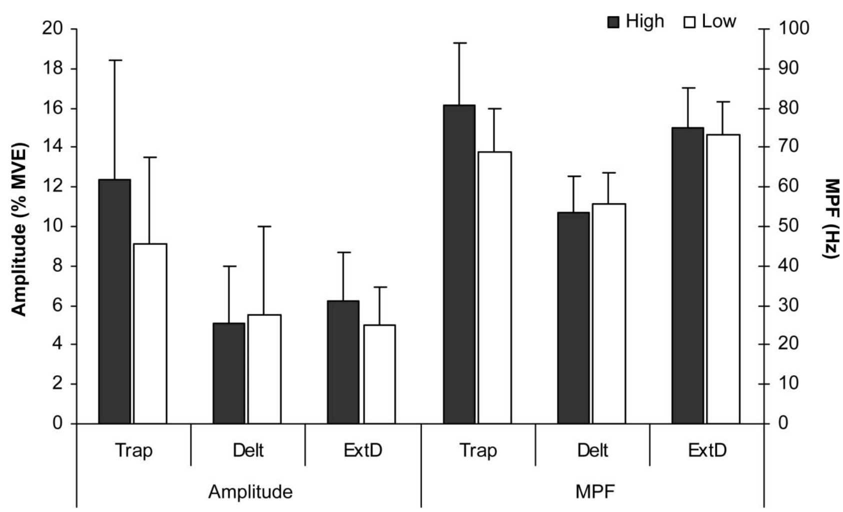
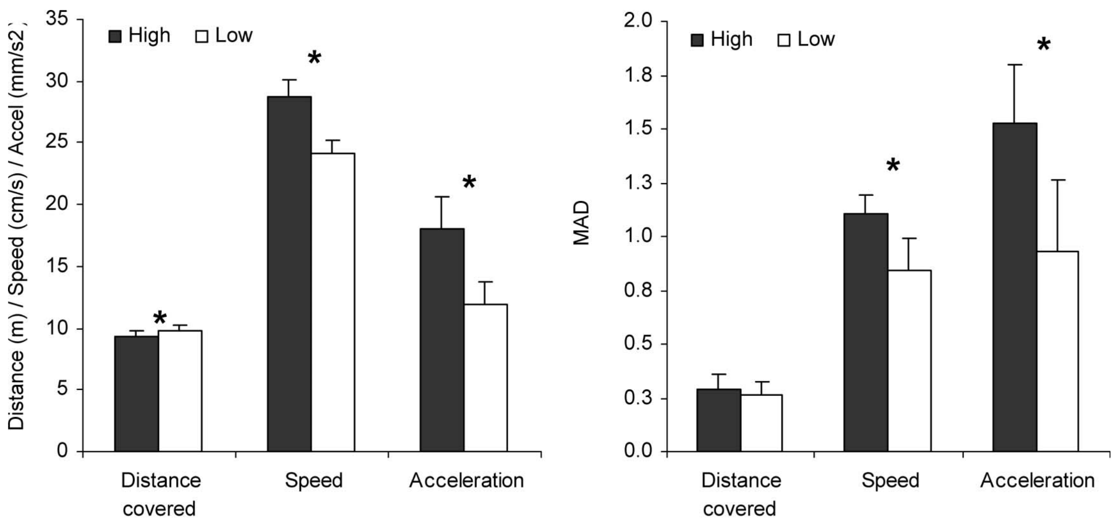


Figure 2. Average electromyographic amplitude and mean power frequency (MPF) for the upper trapezius (Trap), deltoid anterior (Delt) and extensor digitorum (ExtD) muscle in the high and low work pace (error bars indicate SD).

Table 1. Average distance covered and variability in distance covered for the wrist, elbow and shoulder (upper part of the table), as well as the distance covered and their variability for these joints relative to each other (lower part of the table).

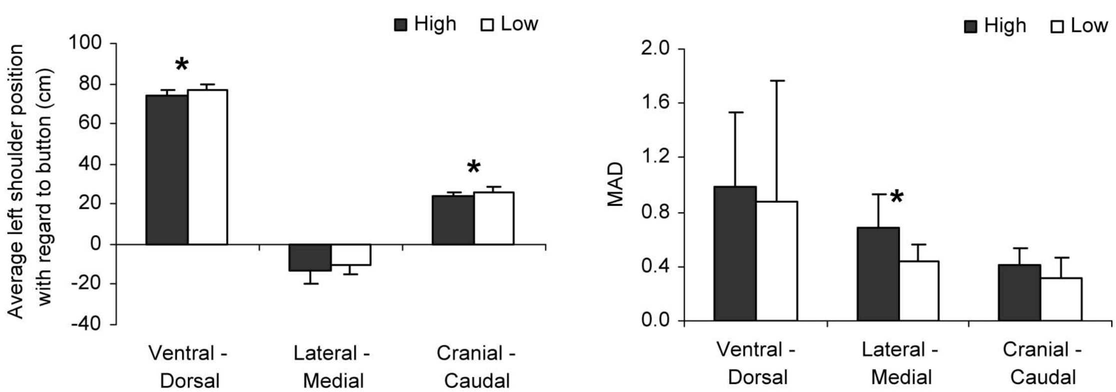
	Average				Variability (MAD)			
	High		Low		High		Low	
Distance covered								
Wrist (m)	**9.30**	(0.4)	**9.83**	(0.4)	0.29	(0.06)	0.26	(0.06)
Elbow (m)	**4.40**	(0.4)	**4.70**	(0.5)	0.22	(0.07)	0.20	(0.04)
Shoulder (m)	1.09	(0.1)	1.11	(0.2)	0.10	(0.04)	0.09	(0.03)
Elbow – shoulder (m)	**4.1**	(0.4)	**4.4**	(0.5)	0.20	(0.06)	0.19	(0.03)
Wrist – shoulder (m)	**9.2**	(0.5)	**9.6**	(0.4)	0.30	(0.10)	0.26	(0.06)
Wrist – elbow (m)	**9.2**	(0.4)	**9.7**	(0.4)	0.28	(0.06)	0.26	(0.06)

MAD = median absolute deviation.
Values refer to total distance covered per work cycle.
Values shown in parentheses indicate standard deviations.
Significant differences between work paces ('high' vs. 'low') are shown in bold ($p < 0.05$).



(a) (b)

Figure 3. (a) Average distance covered, speed and acceleration of the wrist for the high and low work pace; (b) average cycle-to-cycle variability (median absolute deviation (MAD)) for distance covered, speed and acceleration of the wrist. Error bars indicate SD. *$p < 0.05$.



(a) (b)

Figure 4. (a) Average left shoulder position for both conditions in three dimensions. Shoulder position is expressed as the distance of the shoulder with regard to the push button in front of the subject; (b) average cycle-to-cycle variability (median absolute deviation (MAD)) for shoulder position in three dimensions. Error bars indicate SD. *$p < 0.05$.

3.2. Variability

An evident cycle-to-cycle variability was found for all investigated kinetic and kinematic parameters in both the HWP and LWP conditions (Figures 3b, 4b, 6).

The upper trapezius and deltoid EMG amplitude (Figure 6) did not show significant differences in cycle-to-cycle variability ($p = 0.58$, $Z = 0.56$ and $p = 0.40$, $Z = 0.84$) between HWP and LWP. However, the extensor digitorum (Figure 6) showed a significantly larger variability in EMG activity across work cycles in the HWP condition compared with the LWP ($p = 0.012$, $Z = 2.52$).

As expected from the higher average speed and acceleration of the wrist during the HWP, the cycle-to-cycle variability in wrist speed and acceleration was also larger (Figure 3b; $p = 0.017$, $Z = 2.52$ and $p = 0.049$, $Z = 1.96$ respectively). The variability, in distance covered by the wrist, between cycles was not significantly different between conditions (Figure 3b; $p = 0.16$, $Z = 1.4$).

The HWP condition was associated with significantly more variability in the sideward position of the shoulder (Figure 4b; $p = 0.017$, $Z = 2.38$) than the LWP condition and a tendency towards significantly more variability in the upward position

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

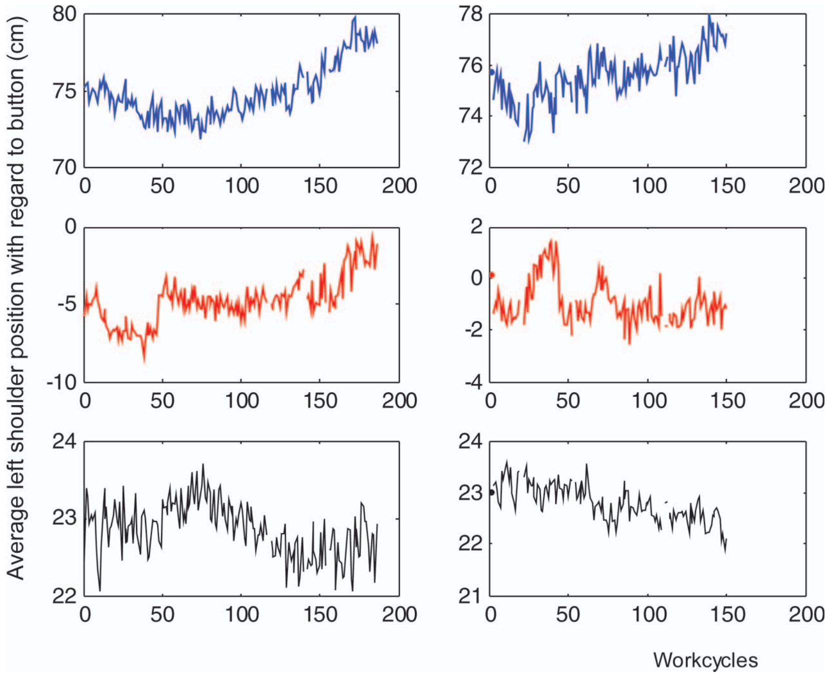


Figure 5. Temporal changes in shoulder posture over time for one subject. Ventral–dorsal (upper), lateral–medial (middle) and cranial–caudal (lower) movements. This subject showed examples of both smooth temporal shifts (upper left) and abrupt shifts in shoulder position (middle left).

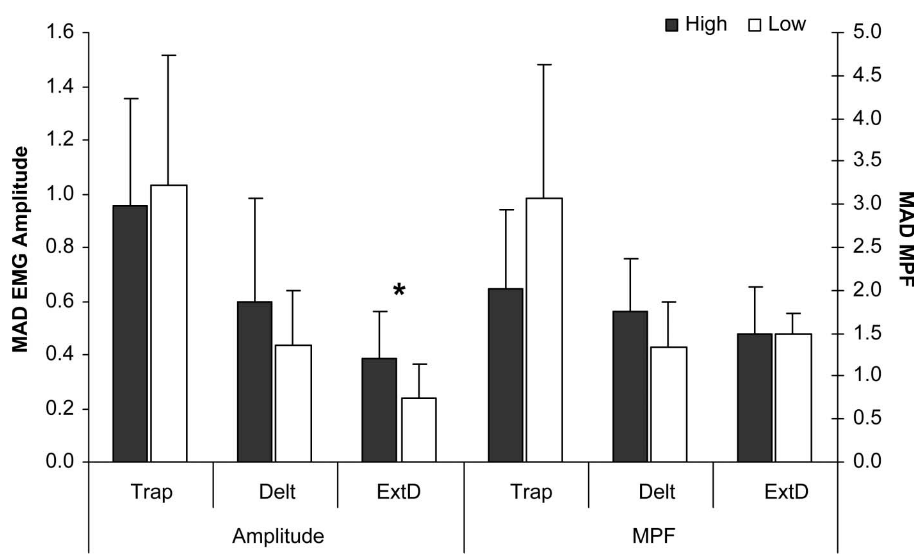


Figure 6. Average cycle-to-cycle variability (median absolute deviation (MAD)) for the electromyographic amplitude and mean power frequency (MPF) of the upper trapezius (Trap), deltoid anterior (Delt) and extensor digitorum (ExtD) muscle in the high and low pace (error bars indicate SD). $*p < 0.05$.

(Figure 4b; $p = 0.067$, $\chi = 1.68$). When the amount of variability in all directions was summarised, six out of eight participants showed more variability in shoulder posture during the HWP condition, but the difference was not statistically significant ($p = 0.16$, $Z = 1.4$).

3.3. Manifestations of fatigue and pain perception

Perceived fatigue increased significantly across time from a Borg scale ranking of 0.3 to about 3.5 in both work paces (Figure 7; $p < 0.001$, $\chi^2 = 58.13$), but the

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

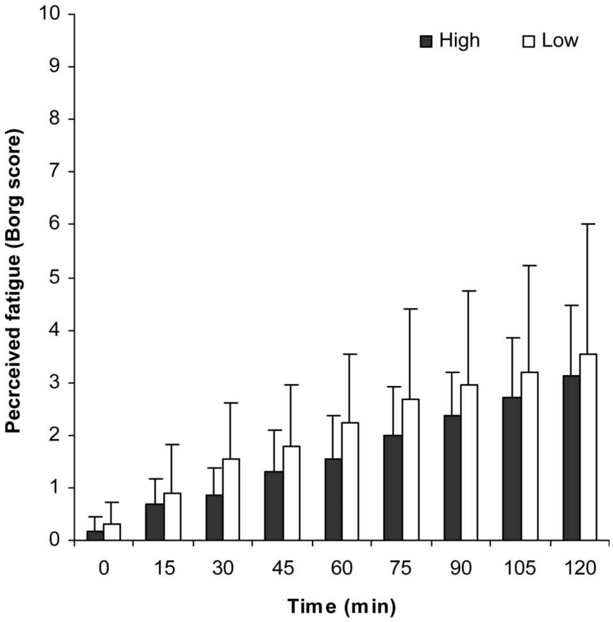


Figure 7. Temporal changes in perceived fatigue in the neck and shoulder area for both work paces averaged across all subjects. Error bars indicate SD.

level of fatigue and its rate of increase did not differ significantly between the LWP and HWP ($p = 0.307$, $Z = 1.4$).

The absolute maximum shoulder abduction force varied widely between participants before the start of both conditions (227–402 N and 214–340 N for the HWP and LWP, respectively). While maximum force had decreased after the work bout for seven participants at both work paces, this change was not statistically significant ($p = 0.12$, $Z = 1.54$). Work pace did not have a significant effect on the decrease in maximum shoulder force ($p = 0.86$, $Z = 0.17$).

In the HWP condition, PPT in the trapezius region decreased to 294 kPa from a pre-exercise mean value of 333 kPa. The corresponding PPT in the deltoid region decreased to 196 kPa from 235 kPa at baseline. In the LWP condition, PPT decreased to 255 and 206 kPa, with baselines at 284 and 235 kPa, for the trapezius and deltoid regions, respectively. The PPT for the upper trapezius region showed a tendency towards a decrease over time ($p = 0.06$, $Z = 1.84$), whereas the deltoid region PPT significantly decreased over time ($p = 0.048$, $Z = 1.98$). No main effect of work pace was found for the two regions ($p = 0.9$, $Z = 0.07$ and $p = 1.0$, $Z = 0$ respectively).

No consistent evidence was found for a development of EMG manifestations of muscle fatigue, in terms of an amplitude increase concomitant with a shift of the frequency spectrum shifts towards lower frequencies (Basmajian and de Luca 1985). EMG amplitude and MPF did change over time in a number of participants, but in an inconsistent way.

Finally, participants made more errors per work cycle during the HWP ($p = 0.017$, $Z = 2.38$) than during the LWP. On average, the number of errors per work cycle was almost double at the HWP (0.67 vs. 0.36). The number of errors did not change significantly ($p = 0.97$, $\chi^2 = 4.08$) across the 2-h work period in any of the conditions.

4. Discussion

The present exploratory study was designed to study effects of work pace in a simulated pick and place task on the level and variability of a number of kinetic and kinematic parameters, as well as on fatigue development. While muscle activity, perceived fatigue and pain sensitivity did not seem to be affected by work pace, participants moved more efficiently at the higher pace, yet with a larger variability. They also made more errors at the higher pace.

4.1. Representativeness of the study

The simulated assembly task performed by the participants was not an exact copy of an existing occupational assembly task. The task was based on the Perdue Pegboard task, which has been used as one of several standardised tasks for assessing proficiency in assembly work (e.g. Tiffin and Asher 1948). The task included common elements of manual assembly work, such as picking, placing and positioning of components (e.g. Krawczyk and Armstrong 1991, de Looze *et al.* 2005). Work technique could, in principle, be decided by the participant, but the task instructions per se allowed for only small deviations from the prescribed work sequence. The average activity of the trapezius muscle corresponded to 10–15%MVC, which is similar to previous field studies on assembly work (e.g. Christensen 1986, Bosch *et al.* 2007). Whereas the basic task could be considered representative for occupational short cycle assembly work, several potential modifiers of motor behaviour occurring in true occupational assembly were controlled in the current laboratory study; for instance, occurrences of non-cyclic work tasks and scheduled or discretionary breaks. Both work paces were similar to industrial standards, corresponding to about 80% and 100% of the work pace expected from experienced workers in industry. The HWP could be considered as a realistic industrial pace, whereas the low one can be seen as a pace typical for a learning phase.

The duration of the present 2-h task is shorter than most work bouts in real life. Task duration could have an effect on several of the investigated variables; for

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

instance, due to accumulating fatigue. On the other hand, a recent review on muscle fatigue development during light manual work by de Looze *et al*. (2009) suggested that task duration did not differ between studies showing manifestations of fatigue and those not doing so. Thus, task duration may not be a critical concern with regard to representativeness.

The experiment was performed by inexperienced young female participants. Even though the simulated assembly work task was relatively easy, learning effects might have affected the motor performance of the participants. However, after analysing the cycle-to-cycle variability in cycle times, no significant difference was found between the first and second measurement day. The training period provided prior to the actual measurements therefore seemed to be long enough to prevent substantial further learning effects. Notably, an increasing number of people work only for short periods (e.g. production peaks) at manufacturing companies (Brewster *et al*. 1997, Franco and Winqvist 2002, Neumann *et al*. 2002) and would thus almost steadily be in a learning phase. Using inexperienced participants, therefore, might not hamper the translation of the results to practice.

The experiment was performed on eight subjects, acting as their own controls. Due to the limited number of participants, results may not readily be generalised to a general population of young, healthy females, let alone subjects of other ages, gender or disorder status. Also, some effects of changed work pace may have been left undetected due to insufficient statistical power. However, besides the EMG results (Figure 6), the numerical sizes of effects in the study that proved to be statistically insignificant do not lead to strong suspicions of type II errors.

4.2. *Work pace and exposure levels*

The current study suggested that the hand was moved more efficiently at a higher work pace level. A more detailed analysis showed that the forearm and upper arm both contributed to this decrease in the movement distance of the wrist, whereas shoulder movement did not seem to contribute. The results did, indeed, show a more forward shoulder position, but the absence of an increased shoulder movement indicates that the upper body in general did not move more in the high pace condition. Maintaining a more inclined upper body posture, which will move the arms and hands closer to the pegboard, could explain the more economic movements in the high pace condition.

Also, the more economic movements in the high pace condition could be a sign of the participant 'throwing' components to shorten movement time. A more detailed analysis of wrist movement did not, however, confirm this explanation; the start and stop positions of the wrist when getting and putting components was similar for both paces. Participants could also have chosen a more comfortable – while less efficient – strategy for putting and getting components in the low pace condition by approaching the bins more vertically. Analysis of the separate trajectories in each of the three orthogonal directions did, indeed, indicate that the total amount of movement in the vertical as well as both horizontal directions was smaller for the HWP condition.

A higher work pace did not result in a higher muscle activity, according to the EMG recordings. This stands in contrast to other experimental work pace studies quantifying workload by electromyography (e.g. Sundelin 1993, Laursen *et al*. 1998). The diverging results might be due to differences between the studied tasks, including differing requirements for speed and acceleration. In the present study, the increased work pace did not result in additional shoulder movement and thus no additional requirements were put on the trapezius muscle for this reason (Kuijt-Evers *et al*. 2007). Also, the more forward, 'engaged' upper body posture during the HWP reduced the external gravitational torque on the moving arms, leading to a smaller force required from the muscles to support the arms. Finally, load sharing between the muscles in the upper extremity may differ between the work paces, including a transfer of activity in the high pace condition to synergistic muscles not recorded by the surface EMG electrodes (Palmerud *et al*. 1998).

The number of errors, measuring the quality of work, doubled when comparing the HWP to the LWP condition. A study by Escorpizo and Moore (2007) showed the same trends; a decrease in cycle time resulted in substantially more errors. Also, the current results are consistent with Fitts Law (Fitts 1954) and an empirical study by Schmidt *et al*. (1979), stating that working at a higher speed will lead to lower accuracy on the target.

4.3. *Work pace and motor variability*

Previous studies on motor variability in occupational tasks have shown that several parameters describing motor patterns vary between cycles, even in simple short-cycle tasks such as lifting (Kjellberg *et al*. 1998, Granata *et al*. 1999, van Dieën *et al*. 2001) or industrial assembly work (Mathiassen *et al*. 2003, Möller *et al*. 2004). The current study confirmed these findings; a cycle-to-cycle variability, as measured by the MAD parameter, was seen in all kinematic variables. To the authors' knowledge, this parameter, which has statistical advantages over, for example, the standard

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

deviation (Chau *et al.* 2005), has not been used before in short-cycle upper extremity work. A quantitative comparison with other studies investigating cycle-to-cycle variability of upper extremity kinematics (e.g. Madeleine *et al.* 2008b) was therefore not possible.

In the present study, an increase in work pace resulted in an increased cycle-to-cycle variability in movement speed and acceleration of the wrist. This finding is consistent with studies on signal-dependent noise (Harris and Wolpert 1998), showing an increase in kinematic variability with an increase in speed. Some recent studies suggest that motor variability can be modified by several additional factors relevant to occupational life. Acute and chronic pain altered the magnitude of motor variability in a simulated meat cutting task (Madeleine *et al.* 2008a). In that study, the authors showed that the development of pain within 6 months after employment was accompanied by less arm and trunk motor variability for a population of inexperienced butchers. Experience in itself had the opposite effect on motor variability; experienced participants showed more variability in trunk and arm kinematics compared with novices.

Since force fluctuations are larger as more motor units are recruited (e.g. Taylor *et al.* 2003, Moritz *et al* 2005), an association can be expected between the level of EMG activity and its variability. This was only partially supported in the current study. For the trapezius and deltoid muscles, the mean activity did not change with work pace and neither did cycle-to-cycle variability. However, the forearm extensor (extensor digitorum) showed more cycle-to-cycle variability in EMG amplitude at a higher work pace, while the average amplitude did not differ between conditions.

4.4. *Work pace and fatigue development*

Since the HWP resulted in shorter cycle times, larger accelerations and higher movement speed, fatigue could have been expected to develop at a faster rate than during the low pace. However, responses were similar in both conditions. Perceived fatigue and PPT changed over time, but no signs of muscle fatigue were found according to standard EMG indicators, i.e. a decreasing MPF and increasing amplitude (Basmajian and de Luca 1985).

In the present study, perceived fatigue levels even tended to be higher during the low pace than during the high pace, which was, at first glance, surprising. However, in a study of a simulated short-cycle pick and place task, Escorpizo and Moore (2007) reported a similar result; discomfort did not increase as cycle time was halved. Also, a study by Krawczyk and Armstrong (1991) on a hand transfer task suggested that perceived fatigue did not have a straightforward relationship with work pace. A few other studies have investigated whether fatigue development during assembly work is related to work pace, yet with diverging results (Sundelin 1993, Mathiassen and Winkel 1996). Moreover, a general perceived fatigue may reflect fatigue dimensions that are not directly related to the physical load, such as sleepiness and lack of motivation (Åhsberg *et al.* 1997) and these factors may have differed to the disadvantage of the low pace.

The absence of clear signs of fatigue, even in the high-pace condition expected to cause at least some fatigue (de Looze *et al.* 2009), opens a hypothesis that some of the kinematic effects of the work pace change may have had a preventive effect on cumulative fatigue development. An early study by Andersson *et al.* (1974) suggested that small postural changes in sitting might have an alleviating effect on fatigue. Recent studies confirm this notion by suggesting that discomfort during sitting is unconsciously prevented by abrupt changes in posture (Vergara and Page 2002, Noro *et al.* 2005). Further support is found in studies by Côté *et al.* (2005), Pigini *et al.* (2008) and Fuller *et al.* (2009). In the two latter studies, analysis of kinematic patterns during a pick and place and a reaching task, respectively, revealed changes in upper extremity postures that were suggested to be triggered by fatigue development. In the study of repetitive hammering by Côté *et al.* (2005), fatigue-related changes were found in elbow kinematics and trunk motion, whereas cycle time and shoulder kinematics were not affected.

In the present experiment, abrupt shifts in posture were observed during both work paces, but discomfort ratings were too infrequent to establish whether these posture shifts had an immediate effect on discomfort. Participants who are not allowed to change technique or who for some reason ignore a developing discomfort might be more at risk of developing muscle fatigue. It might be hypothesised that constrained kinematics obstructs temporal changes in regional muscle activity patterns that could counteract cumulative fatigue development, as indicated by recent EMG studies. Thus, Farina *et al.* (2008) showed that larger changes in the spatial distribution of EMG amplitude within the upper trapezius muscle was associated with less fatigue during an isometric contraction. In another study, Falla and Farina (2007) showed that such changes in the spatial distribution of electromyography could be triggered by short increases in muscle loading, consistent with earlier studies indicating that short bursts of activity on top of an isometric contraction may stimulate motor unit substitution (Westad *et al.* 2003). A recent study by van Dieën *et al.* (2009)

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

showed that more variability in the EMG amplitude of the back extensor muscles resulted in less fatigue development, consistent with an earlier finding that participants with a better ability to alternate activity between parts of the lumbar extensor muscles had better endurance in isometric back extension (van Dieën *et al*. 1993). Some authors have even suggested that individuals who are able to effectively utilise intrinsic opportunities to obtain motor variability are less susceptible to musculoskeletal disorders (Kilbom 1994, Mathiassen and Aminoff 1997, Mathiassen 2006, Madeleine *et al*. 2008a).

The current study focused the biomechanical analysis on the assembly part of the experimental task but, as a hypothesis, the somewhat heavier pegboard lifting action at the end of the work cycle might have had a preventive effect on fatigue development per se. In real-life assembly work, opportunities to vary muscle forces and postures will be even more extensive, which can explain that many studies have failed to demonstrate fatigue, even after hours of work at muscle activity levels that are, on average, compatible with those leading to substantial fatigue after few minutes of isometric activity (de Looze *et al*. 2009).

5. Conclusions

- In industrial engineering, an increased work pace may be realised in order to increase human performance. Increasing the work pace might, however, lead to more production disturbances, even in the absence of fatigue among the workers, as suggested by an increasing number of errors. In the present study, errors represented non-productive incidents such as dropping components or putting components in the wrong bin. Errors were corrected by the participants and so did not have any effect on the final quality of the work. On the other hand, these non-productive incidents might affect work rhythm and process flow and, in high-risk environments, they may have serious consequences.
- The present study showed some, if not a dramatic, cycle time variability within participants, but in less controlled assembly work this variability is probably larger. Work pace did not have an effect on the magnitude of cycle time variability, indicating that time losses in production caused by this variability will not be sensitive to the average work pace within the range studied.
- The results in the current study do not suggest directly negative physiological effects on operators of an increased work pace. Changing the work pace within the limits investigated here seemed not to influence average workload and it did not lead to pronounced fatigue. Thus, work pace may have less impact on average workload than other organisational factors, such as work duration. While an increased work pace led to a larger motor variability, it is not suggested that a higher work pace is used as an intervention to stimulate variation, since it will also increase the frequency of repeated actions. Other measures, such as job rotation, have the intrinsic property to increase variation in workload without also increasing the repetitiveness of the task.

Acknowledgements

We would like to thank Oeds van der Wijk for supporting the RWF analysis. This work was financially supported by the Centre for Musculoskeletal Research in Sweden and Body at Work, the Dutch Research Center for Physical Activity, Work and Health.

References

Åhsberg, E. and Gamberale, F., 1998. Perceived fatigue during physical work: an experimental evaluation of a fatigue inventory. *International Journal of Industrial Ergonomics*, 21, 117–131.

Åhsberg, E., Gamberale, F., and Kjellberg, A., 1997. Perceived quality of fatigue during different occupational tasks. Development of a questionnaire. *International Journal of Industrial Ergonomics*, 20, 121–135.

Andersen, J.H., *et al*., 2003. Risk factors in the onset of neck/shoulder pain in a prospective study of workers in industrial and service companies. *Occupational and Environmental Medicine*, 60, 649–654.

Andersson, G.B.J., *et al*., 1974. Lumbar disc pressure and myoelectric backmuscle activity durings itting. *Scandinavian Journal of Rehabilitation Medicine*, 6, 101–121.

Arndt, R., 1987. Work pace, stress, and cumulative trauma disorders. *American Journal of Hand Surgery*, 12, 866–869.

Bartlett, R., Wheat, J., and Robins, M., 2007. Is movement variability important for sports biomechanists? *Sports Biomechanics*, 6, 224–243.

Basmajian, J.V. and de Luca, C. J ., 1985. *Muscles alive: Their functions revealed by electromyography*. 5th edn. Baltimore: Lippincott, Williams and Wilkins.

Bergqvist, U., *et al*., 1995. Musculoskeletal disorders among visual display terminal workers: individual, ergonomic, and work organizational factors. *Ergonomics*, 38 (4), 763–776.

Bernard, P., 1997. *Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity and low back*. Cincinnati Ohio: NIOSH.

Bongers, P.M., Kremer, A.M., and ter Laak, J., 2002. Are psychosocial factors, risk factors for symptoms and signs of the shoulder, elbow, or hand/wrist? A review of the epidemiological literature. *American Journal of Industrial Medicine*, 41 (5), 315–342.

Borg, G.A., 1982. Psychophysical bases of perceived exertion. *Medicine & Science in Sports & Exercise*, 14 (5), 377–381.

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

Bosch, T., de Looze, M.P., and van Dieën, J.H., 2007. Development of fatigue and discomfort in the upper trapezius muscle during light manual work. *Ergonomics*, 50 (2), 161–177.

Brewster, C., Mayne, L., and Tregaskis, O., 1997. Flexible working in Europe: a review of the evidence. *Management International Review*, 37, 85–103.

Chau, T., Young, S., and Redekop, S., 2005. Managing variability in the summary and comparison of gait data. *Journal of Neuroengineering and Rehabilitation*, 29, 2–22.

Christensen, H., 1986. Muscle activity and fatigue in the shoulder muscles of assembly-plant employees. *Scandinavian Journal of Work, Environment & Health*, 12 (6), 582–587.

Côté, J.N., *et al*., 2005. Differences in multi- joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clinical Biomechanics*, 20, 581–590.

de Looze, M.P., Bosch, T., and van Dieën, J.H., 2009. Manifestations of shoulder fatigue in prolonged activities involving low-force contractions. *Ergonomics*, 52 (4), 428–437.

de Looze, M.P., *et al*., 2005. Productivity and discomfort in assembly work: the effect of an ergonomic workplace adjustment at Philips DAP. *In*: P. Vink, ed. *Comfort and design: principles and good practice*. Boca Raton: CRC Press, 129–136.

Dempsey, P.G. and McGorry, R.W., 2004. Investigation of a pork shoulder deboning operation. *Journal of Occupational and Environmental Hygiene*, 1 (3), 167–172.

Domkin, D., *et al*., 2005. Joint angle variability in 3D bimanual pointing: uncontrolled manifold analysis. *Experimental Brain Research*, 163, 44–57.

Escorpizo, R. and Moore, A., 2007. The effects of cycle time on the physical demands of a repetitive pick-and-place task. *Applied Ergonomics*, 38 (5), 609–615.

Farina, D., *et al*., 2002. Standardising surface electromyogram recordings for assessment of activity and fatigue in the human upper trapezius muscle. *European Journal Applied Physiology*, 86 (6), 469–478.

Farina, D., *et al*., 2003. Effect of side dominance on myoelectric manifestations of muscle fatigue in the human upper trapezius muscle. *European Journal Applied Physiology*, 90, 480–488.

Farina, D., *et al*., 2008. The change in spatial distribution of upper trapezius muscle activity is correlated to contraction duration. *Journal of Electromyography and Kinesiology*, 18, 16–25.

Falla, D. and Farina, D., 2007. Periodic increases in force during sustained contraction reduce fatigue and facilitate spatial redistribution of trapezius muscle activity. *Experimental Brain Research*, 182 (1), 99–107.

Fischer, A.A., 1987. Pressure threshold measurement for diagnosis of myofascial pain and evaluation of treatment results. *Clinical Journal of Pain*, 2, 207–214.

Fitts, P., 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47 (6), 381–391.

Franco, A. and Winqvist, K., 2002. *At the margins of the labour market? Women and men in temporary jobs in Europe. Statistics in focus: Population and social conditions*. Luxembourg: European Communities, Eurostat.

Fuller, J.R., *et al*., 2009. Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. *Journal of Electromyography and Kinesiology*, 19, 1043–1052.

Granata, K.P., Marras, W.S., and Davis, K.G., 1999. Variation in spinal load and trunk dynamics during repeated lifting exertions. *Clinical Biomechanics*, 14 (6), 367–375.

Hammarskjöld, E., Ekholm, J., and Harms-Ringdahl, K., 1989. Reproducibility of work movements with carpenters' hand tools. . *Ergonomics*, 32, 1005–1018.

Harris, C.M. and Wolpert, D.M., 1998. Signal-dependent noise determines motor planning. *Nature*, 394 (6695), 780–784.

Hermens, H.J., *et al*., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology*, 10, 361–374.

Hidalgo-Lozano, A., *et al*., 2010. Muscle trigger points and pressure pain hyperalgesia in the shoulder muscles in patients with unilateral shoulder impingement: a blinded, controlled study. *Experimental Brain Research*, 202, 915–925.

Houtman, I.L.D., *et al*., 1994. Psychosocial stressors at work and musculoskeletal problems. *Scandinavian Journal of Work Environment and Health*, 20, 139–145.

Jackson, J.A., Mathiassen, S.E., and Dempsey, P.G., 2009. Methodological variance associated with normalization of occupational upper trapezius EMG using submaximal reference contractions. *Journal of Electromyography and Kinesiology*, 19, 416–427.

Järvi, M. and Uusitalo, T., 2004. Job rotation in nursing: a study of job rotation among nursing personnel from the literature and via a questionnaire. *Journal of Nursing Management*, 12 (5), 337–347.

Jensen, C., Vasseljen, O., and Westgaard, R.H., 1993. The influence of electrode position on bipolar surface electromyogram recordings of the upper trapezius muscle. *European Journal Applied Physiology*, 67, 266–273.

Jensen, C. and Westgaard, R.H., 1997. Functional subdivision of the upper trapezius muscle during low-level activation. *European Journal Applied Physiology*, 76, 335–339.

Kilbom, A., 1994. Repetitive work of the upper extremity. Part II: the scientific basis (knowledge base) for the guide. *International Journal of Industrial Ergonomics*, 14, 59–86.

Kjellberg, K., Lindbeck, L., and Hagberg, M., 1998. Method and performance: two elements of work technique. *Ergonomics*, 41, 798–816.

Krawczyk, S. and Armstrong, T.J., 1991. Perceived exertion over time of hand transfer tasks: weight, frequency, and distance. *In*: Y. Queinnec and F. Daniellou, eds. *Designing for everyone*. Taylor & Francis, 167–169.

Kuijt-Evers, L.F., *et al*., 2007. Association between objective and subjective measurements of comfort and discomfort in hand tools. *Applied Ergonomics*, 38 (5), 643–654.

Laursen, B., Jensen, B.R., and Sjøgaard, G., 1998. Effect of speed and precision demands on human shoulder muscle electromyography during a repetitive task. *European Journal Applied Physiology*, 78 (6), 544–548.

Madeleine, P. and Madsen, T.M.T., 2009. Changes in the amount and structure of motor variability during a deboning process are associated with work experience and neck–shoulder discomfort. *Applied Ergonomics*, 40 (5), 887–894.

Madeleine, P., Mathiassen, S.E., and Arendt-Nielsen, L., 2008a. Changes in the degree of motor variability associated with experimental and chronic neck-shoulder pain during a standardized repetitive arm movement. *Experimental Brain Research*, 185, 689–698.

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011

Madeleine, P., Voigt, M., and Mathiassen, S.E., 2008b. Cycle-to-cycle variability in biomechanical exposure among butchers performing a standardised cutting task. *Ergonomics*, 51, 1078–1095.

Mathiassen, S.E., 2006. Diversity and variation in biomechanical exposure: what is it, and why would we like to know? *Applied Ergonomics*, 37 (4), 419–427.

Mathiassen, S.E. and Aminoff, T., 1997. Motor control and cardiovascular responses during isoelectric contractions of the upper trapezius muscle. *European Journal Applied Physiology*, 76, 434–444.

Mathiassen, S.E., Möller, T., and Forsman, M., 2003. Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics*, 46, 800–824.

Mathiassen, S.E. and Winkel, J., 1990. Electromyographic activity in the shoulder-neck region according to arm position and glenohumeral torque. *European Journal Applied Physiology*, 61, 370–379.

Mathiassen, S.E. and Winkel, J., 1996. Physiological comparison of three interventions in light assembly work: reduced work pace, increased break allowance and shortened working days. *International Archives of Occupational and Environmental Health*, 68, 94–108.

Mathiassen, S.E., Winkel, J., and Hägg, G., 1995. Normalization of surface EMG amplitude from the upper trapezius muscle in ergonomic studies – a review. *Journal of Electromyography and Kinesiology*, 5, 197–226.

Mathiassen, S.E., *et al.*, 1993. Biochemical indicators of hazardous shoulder-neck loads in light industry. *Journal of Occupational Medicine*, 35, 404–407.

Möller, T., *et al.*, 2004. Job enlargement and mechanical exposure variability in cyclic assembly work. *Ergonomics*, 47, 19–40.

Moritz, C., *et al.*, 2005. Discharge rate variability influences the variation in force fluctuations across the working range of a hand muscle. *Journal of Neurophysiology*, 93, 2449–2459.

Nakata, M., Hagner, I.M., and Jonsson, B., 1993. Trapezius muscle pressure pain threshold and strain in the neck and shoulder regions during repetitive light work. *Scandinavian Journal of Rehabilitation Medicine*, 25 (3), 131–137.

National Research Council/Institute of Medicine, 2001. *Musculoskeletal disorders and the workplace – Low back and upper extremities*. Washington DC: National Academy Press.

Neumann, W.P., *et al.*, 2002. A case study evaluating the ergonomic and productivity impacts of partial automation strategies in the electronics industry. *International Journal of Production Research*, 40 (16), 4059–4075.

Niebel, B. and Freivalds, A., 2003. *Methods, standards, and work design*. 11th ed. Boston: McGraw-Hill.

Nielsen, P.K., *et al.*, 2010. Effect of physical training on pain sensitivity and trapezius muscle morphology. *Muscle Nerve*, 41, 836–844.

Noro, K., Fujimaki, G., and Kishi, S., 2005. A theory on pressure distribution and seat discomfort. *In*: P. Vink, ed. *Comfort and design: principles and good practice*. Boca Raton: CRC Press, 129–136.

Odenrick, P., *et al.*, 1988. Influence of workpace on trapezius activity in assembly-line work. *In*: A.S. Adams, R.R. Hall, B. McPhee, and M. Oxenburgh, eds. *In Proceedings of the 10th congress of the International Ergonomics Association*. Sydney: Ergonomics Society of Australia, 418–420.

Palmerud, G., *et al.*, 1995. Voluntary redistribution of muscle activity in human shoulder muscles. *Ergonomics*, 38, 806–815.

Palmerud, G., *et al.*, 1998. Consequences of trapezius relaxation on the distribution of shoulder muscle forces: an electromyographic study. *Journal of Electromyography and Kinesiology*, 8 (3), 185–193.

Pigini, L., *et al.*, 2008. Long term analysis of kinematic pattern during a repetitive work task using upper limbs. *Gait & Posture*, 28 (1), S17–S18.

Schmidt, R.A., *et al.*, 1979. Motor output variability: a theory for the accuracy of rapid motor acts. *Psychology Review*, 47, 415–451.

Selen, L.P.J., van Dieën, J.H., and Beek, P.J., 2006. Impedance modulation and feedback corrections in tracking targets of variable size and frequency. *Journal of Neurophysiology*, 96 (5), 2750–2759.

Shevlyakov, G. and Vilchevski, N., 2002. *Robustness in data analysis*. Utrecht: VSP.

Straker, L.M., 2003. A review of research on techniques for lifting low-lying objects: evidence for a correct technique. *Work*, 20 (2), 83–96.

Strimpakos, N., *et al.*, 2005. Issues in relation to the repeatability of and correlation between EMG and Borg scale assessments of neck muscle fatigue. *Journal of Electromyography and Kinesiology*, 15 (5), 452–465.

Sundelin, G., 1993. Patterns of electromyographic shoulder muscle fatigue during MTM paced repetitive arm work with and without pauses. *International Archives of Occupational and Environmental Health*, 64, 485–493.

Taylor, A.M., Christou, E.A., and Enoka, R.M., 2003. Multiple features of motor-unit activity influence force fluctuations during isometric contractions. *Journal of Neurophysiology*, 90, 1350–1361.

Terrier, P. and Schutz, Y., 2003. Variability of gait patterns during unconstrained walking assessed by satellite positioning (GPS). *European Journal Applied Physiology*, 90, 554–561.

Thorn, S., *et al.*, 2002. Low-threshold motor unit activity during a 1-h static contraction in the trapezius muscle. *International Journal of Industrial Ergonomics*, 30, 225–236.

Tiffin, J. and Asher, E.J., 1948. The Purdue Pegboard: norms and studies of reliability and validity. *Journal of Applied Psychology*, 32 (3), 234–247.

Trinkoff, A.M., *et al.*, 2006. Longitudinal relationship of work hours, mandatory overtime, and on-call to musculoskeletal problems in nurses. *American Journal of Industrial Medicine*, 49 (11), 964–971.

van Dieën, J.H., Oude Vrielink, H.H., and Toussaint, H.M., 1993. An investigation into the relevance of the pattern of temporal activation with respect to erector spinae muscle endurance. *European Journal of Applied Physiology and Occupational Physiology*, 66 (10), 70–75.

van Dieën, J.H., *et al.*, 2001. Within-subject variability in low-back load in a repetitively performed, mildly constrained lifting task. *Spine*, 26, 1799–1804.

van Dieën, J.H., *et al.*, 2009. Low-level activity of the trunk extensor muscles causes electromyographic manifestations of fatigue in absence of decreased oxygenation. *Journal of Electromyography and Kinesiology*, 19 (3), 398–406.

Visser, B., *et al.*, 2004. Effects of precision demands and mental pressure on muscle activation and hand forces in computer mouse tasks. *Ergonomics*, 47, 202–217.

Vergara, M. and Page, A.I., 2002. Relationship between comfort and back posture and mobility in sitting-posture. *Applied Ergonomics*, 33, 1–8.
Welch, P.D., 1967. The use of fast Fourier transforms for the estimation of power spectra: a method based on time averaging over short modified periodograms. *IEEE Transactions on Audio and Electroacoustics*, 15, 70–73.
Wells, R., *et al.*, 2007. Time – a key issue for musculoskeletal health and manufacturing. *Applied Ergonomics*, 38, 733–744.
Westad, C., Westgaard, R.H., and de Luca, C.J., 2003. Motor unit recruitment and derecruitment induced by brief increase in contraction amplitude of the human trapezius muscle. *Journal of Physiology*, 15 (552 (Pt2)), 645–656.
Wild, R., 1994. *Production and operations management*. London: Cassell.
Wilson, C., *et al.*, 2008. Coordination variability and skill development in expert triple jumpers. *Sports Biomechanics*, 7, 2–9.

Downloaded by [Vrije Universiteit Amsterdam] at 00:11 31 August 2011